BENEFITS AND COSTS OF ULTRAVIOLET FLUORESCENT LIGHTING

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ABSTRACT

Objective: To demonstrate the improvements in detection and recognition distances using fluorescent roadway delineation and auxiliary ultra-violet (UVA) headlights and determine the reduction in crashes needed to recover increased costs of the UVA/flourescent technology.

Methods: Field study comparisons with and without UVA headlights. Crash types potentially reduced by UVA/flourescent technology were estimated using annual crash and injury incidence data from the General Estimates System (1995-1996) and the 1996 Fatality Analysis Reporting System. Crash costs were computed based on body region and threat-to-life injury severity.

Results: Significant improvements in detection and recognition distances for pedestrian scenarios, ranging from 34% to 117%. A 19% reduction in nighttime motor vehicle crashes involving pedestrians or pedal-cycles will pay for the additional UVA headlight costs. Alternatively, a 5.5% reduction in all relevant nighttime crashes will pay for the additional costs of UVA headlights and fluorescent highway paint combined.

Conclusions: If the increased detection and recognition distances resulting from using UVA/flourescent technology as shown in this field study reduce relevant crashes by even small percentages, the benefit cost ratios will still be greater than 2; thus, the UVA/flourescent technology is very cost-effective and a definite priority for crash reductions.

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Nighttime driving is one of the motorist's most difficult tasks. The risk of having a crash at night is 2 to 3 times greater than during the daytime. [MacAuley, 1989] Since the basic difference between night and day driving is the absence of light at night, the increase in the accident rate in periods of darkness can be largely attributed to poor visibility conditions. During nighttime driving, visibility depends largely upon the availability of artificial light, either the vehicle headlamps or fixed overhead lighting. [Vanstrum, Landen, 1984] High object visibility is an essential characteristic of traffic control devices and a significant factor in highway safety. Researchers have studied this problem, looking for ways to make objects and pedestrians more visible at night. The use of ultraviolet (UVA) headlamps combined with low beams has been suggested as a promising solution to this problem.

In its research, Ultralux, a UVA headlamp manufacturer, found that pedestrians and other unprotected road users are more easily seen when they are illuminated by UVA lighting.[Ultralux, 1994] Different clothes, depending on the material and color, have different levels of fluorescence. Jeans could be seen at approximately 100m (328ft), for example, while white cotton clothes and synthetic fabrics could be seen at even greater distances. Dark clothes like black wool, however, were no more visible with UV light than with normal low beams. Ultralux also found that washing can improve the fluorescent properties of garments due to the optical whiteners present in many detergents.

One of the most comprehensive studies of detection distances to obstacles on the road when using UVA headlights was conducted by Helmers et al. (1993). The study investigated whether low beam illumination supplemented by UVA headlamps could provide increased detection distances. The result showed a minor, but non-significant increase in detection distances for black and light gray targets. However, detection distances for white targets were twice as long when the low beam headlights were supplemented by UVA lighting.

Several studies indicate that UVA headlamps can increase detection distances considerably, particularly those to pedestrians, compared with the use of only ordinary low beams [Fast et al., 1994 and Staehl, Oxley, Berntman et al.,1994]. Even with clothes of relatively low fluorescent efficiency, detection distance may increase from 50m (164ft) to approximately 100m (328ft) in the presence of glare from oncoming cars, as demonstrated by Fast et al. (1994).

This paper presents the results of a field study comparison of US low beam headlights with and without supplemental UVA headlights. The cost-benefit analysis will focus on the percent reduction in crashes required to recover the increased cost of fluorescent roadway delineation and ultra-violet (UVA) headlights. There are currently no studies of crash reductions due to UVA vehicle headlights which would allow us to compute a "true" cost benefit ratio. Instead we computed estimated costs of implementing UVA /fluorescent technology and compared these to the costs of crashes which could potentially be reduced using this technology. The reduction in crashes needed to pay for the intervention costs, what we call the break-even point, was then computed.

METHODS

FIELD STUDY PROCEDURES - A field study comparing US low beam headlights alone and low beams with supplemental UVA headlights was conducted. [Nitzburg, Knoblauch, Turner, 1999] Test sites were located on the grounds of the Federal Bureau of Investigation's driver training facility in Quantico, Virginia. New pavement marking thermoplastic with UVA activated fluorescent pigment and glass beads was installed at the test sites. The test track consisted of a 1.6km (1.1mi) oval track which was primarily a two lane roadway. The pavement markings included white solid edge lines and double solid yellow center lines. The track widened to four lanes on the southern side of the course. There was no overhead lighting. The testing equipment included two specially equipped research vehicles. Both vehicles were fitted with auxiliary UVA headlight units from Ultralux. The UVA lighting units were used to supplement the regular US low beam headlights. A total of 38 subjects ranging in age from 18 to 76 were tested. The mean age was 40.5 years. Ten of the subjects were 55 years of age or older. There were 16 males and 22 females. Testing typically started between 9:00 p.m. and 9:30 p.m. and concluded between 11:30 p.m. and midnight. Detection and recognition distances were evaluated for roadway delineation, roadway scenes, and pedestrian scenes.

COST-BENEFIT ANALYSIS - To estimate injury incidence, we followed the procedure in Miller, Lestina, and Spicer (1998), which is similar to Blincoe and Faigin (1992), Miller and Blincoe (1994), Miller, Galbraith, Lestina, et al. (1997), and Blincoe (1996). We began with a sample of nonfatal motor vehicle-related injury crashes by sampling strata and police-reported injury severity from NHTSA's 1996 General Estimates System (GES). [NHTSA, 1994] GES does not contain the information on body region injured and injury severity as described by the Maximum Abbreviated Injury Scale (MAIS) which is needed to apply costs. NHTSA's Crashworthiness Data System (CDS), (1995) and National Accident Sampling System (NASS; since renamed the National Automotive Sampling System) (1987) describe these crash injury details. We used 1988-1991 data from CDS for the description of injuries to passenger vehicle occupants involved in towaway crashes. The most recent medical description available of non-CDS nonfatal crash victims (passengers of vehicles other than towed passenger vehicles) came from 1982-

1986 NASS. Multi-year data were needed to obtain large enough samples of injury victims by body region and MAIS severity to accurately determine the incidence of rare injuries like paralyzing spinal cord injuries. We used 1996 GES data to weight CDS and NASS data so they would represent the 1996 nonfatal injury total. Since the CDS and NASS data were collected, many changes such as air bags and increased seat belt use have occurred that influence passenger and non-occupant traffic safety. In developing GES weights to apply to these data, we controlled for police-reported injury severity, age of the victim, and restraint use (belted, unbelted, unknown, in a child seat). Thereby, we had a hybrid CDS/NASS file with weights that summed to estimated annual GES nonfatal incidence by police-reported injury severity, restraint use, and vehicle type. Fatality counts came from the 1996 Fatality Analysis Reporting System (FARS). [NHTSA, 1993]

We then estimated the total cost of these crashes. Costs per crash-involved person by MAIS and body region were merged on the file. The crash costs used are described in Miller at al. (1997), Blincoe(1996) and Miller (1997). Total crash costs include direct costs, which are actual dollar expenditures related to crash injury and damage and indirect. Direct costs include amounts spent for 1) medical care–hospital, physician, rehabilitation, prescription, and related medical costs; 2) work loss–short-term work loss, employer productivity loss and travel delay; and 3) property damage–cost to repair or replace damaged vehicles and property. Indirect costs include are the costs attributed to quality adjusted life years (QALYs) lost. A review of the field study results are included. The increases in detection and recognition distances were used to estimate possible crash reductions.

RESULTS

FIELD STUDY RESULTS

<u>Roadway Delineation</u> - Detection distance and recognition distance measuring procedures were developed for three different types of roadway delineation: right curve, start of a no passing zone and a pedestrian crosswalk. In these procedures, detection distance was defined as the point where subjects indicated they could see the specific target ahead but could not positively identify it as such (e.g., "I think I can see the crosswalk"). The percentage improvement was computed by dividing the increase in detection distance associated with the UVA headlights(in conjunction with the US headlights) by the detection distance associated with the US headlights alone. The UVA headlights outperformed the US headlights for all roadway delineation scenarios. The percentage improvement ranged from 54 percent for the pedestrian crosswalk to 32 percent for the no-passing zone to 6 percent for the right curve. While the differences for both the crosswalk and the no passing zone were significant ($p < .001$), the

results for the right curve were not significant (p = .074). The right curve scene was on a slight downhill section that resulted in very long—over 213m (700ft)— detection distances for both the UVA and the US headlights. The UVA headlights appeared to offer less of an advantage in that situation.

Recognition distances were defined as the point where the subjects were "absolutely sure" that they could see the target stimulus. The percentage improvement in recognition distance was computed similarly as for detection distances. The percentage improvement in recognition distances with UVA headlights are as follows:

Delineation	Percent Improvement
No Passing Zone	48%
Crosswalk	48%
Left Curve, with glare	40%
Left Curve, no glare	21%
Right Curve	14%

All of these differences were significant at the .001 level or better. Because respondents were told that they were looking for a left curve in the road ahead, the left curve scene was not included in the detection task. In the left curve visibility test, the UVA headlights were even more effective when glare from an oncoming vehicle was present (40 percent) than when no such glare was present (21 percent).

Roadway Scenes - Detection distances were determined for 3 different visual stimuli included in 2 roadway scenes: a fluorescent bicycle, and a vehicle and fluorescent traffic cones(both part of a disabled vehicle scene). Visibility improvements with the UVA lighting are very impressive. The percentage improvements for the 3 stimuli are:

Scene	Percent Improvement
Bicycle	284%
Traffic Cones	373%
Disabled Vehicle	27%

Although these improvements are very dramatic, it should be noted that both the bicycle and the traffic cones did not have a retro-reflective component Although retro-reflective materials are visible from relatively long distances without UVA headlights, they provide no visual cues as to the identity of the object marked with the retro-reflective material. With UVA/flourescent technology the entire object is visible, not a small bit of retroflective material. The differences between US and UVA headlights were significant for both the bicycle and the traffic cones, but not for the disabled vehicle. This is possibly because of the intrinsic differences between the test scenes. Both the bicycle (part of a scene with a child pedestrian) and the traffic cones were fluorescent and therefore detectable at relatively long distances with the UVA headlights. Except for the fluorescent traffic cones, the disabled vehicle scene was created to be a worst case scenario. The disabled vehicle was dark colored with no fluorescent or retro reflective component. The tall standing pedestrian cutout had very dark clothing making it difficult to see. Only the squatting pedestrian had a light-colored shirt that provided some visual cues to the subject relative to shape and positioning. Additionally, given that the visual exposure was limited by a windshield shutter, subjects may not have had enough time to focus on both the fluorescent traffic cones and the other disabled scene components. The detection distance differences demonstrate that UVA/fluorescent technology does not work as well in some situations as it does in others.

Recognition distances were determined for the same three stimuli. Improvements in recognition distances were very dramatic in 2 of the 3 cases. The fluorescent bicycle was recognizable at 123m (403ft) with UVA and 39m (127ft) with US headlights—a 218 percent improvement ($p < .001$). The fluorescent traffic cones were recognizable at 91m (300ft) with UVA headlights and 12m (39ft) with US headlights—a very dramatic 680 percent improvement ($p < .001$). The more visually complex disabled vehicle scene was recognized at 33m (108ft) sooner with the US headlights compared with the UVA headlights. Although this 30 percent increase was not statistically significant, it does suggest that the additional cues provided by the UVA lighting do not necessarily help drivers in all situations.

<u>Pedestrian Scenes</u> - Detection and recognition distances were determined for five different pedestrian cutouts. In addition, recognition distances for a dynamic walking pedestrian was included. Improvements in detection distances with the UVA headlight ranged from 20m to 140m (67ft to 459ft); percentage improvements varied from 34 percent to 117 percent. Four of the five differences were significant at the .01 level or better. For the recognition task, four of the five pedestrian cutouts were seen at significantly greater distances with the UVA headlights. These distances were for 15m (50ft) to 59m (193ft) more and represent a 37 percent to 68 percent improvement. The walking pedestrian was visible at 153m (500ft) with the UVA headlight and only 61m (200ft) with the US headlights—a 150 percent increase.

Some of the pedestrian cutouts were tested in a scene with a fluorescent painted bicycle. The bicycle was so highly visible with the UVA headlights that the subjects may have been distracted by its presence, long after they positively identified it as a bicycle. The high visibility of the bicycle in the scene may have distracted from the other objects in the scene.

INTERVENTION COSTS

This analysis used costs for UVA/fluorescent devices provided by the Federal Highway Administration. Estimated highway striping paint costs are $0.11/ft for regular paint and $0.15/ft for fluorescent paint. UVA headlights would be an additional $100.00 per vehicle. Number of vehicle registrations were obtained from 1994 Highway Statistics. [FHWA, 1994]

The miles striped were computed using data on U.S. lane miles and U.S. road miles, excluding local roads. The combination of these will give us the total line miles to be striped. This includes lane markings and center line markings. We computed total relevant U.S. line miles, including lane lines and center lines--to be 1,089,800 miles. Paint for line striping was given a one year life. Table 1 summarizes the intervention costs of UVA/fluorescent technology using the above estimates.

Table 1. Costs for fluorescent lane striping and UVA headlights

Incremental Costs for Fluorescent Striping Paint:	$0.04/ft/year x 5280 ft/mile = $211/mile
U.S. Line Miles, excluding local roads:	1,089,800 miles
Total added cost of highway paint striping with fluorescent paint:	$230 million
Head Light Costs for Fluorescent Headlights: annualized over an 8 year period:	$100.00 $ 13.83/year
Number of Vehicles:	189,500,000
Annualized Headlight Costs for all Vehicles:	$2,621 million
Cost of Headlights + Striping:	$2,851 million

CRASH COSTS

We identified crash geometries where the use of UVA vehicle headlights might reduce the frequency or severity. Because UVA headlights will not reduce daylight crashes, they were excluded from our analysis. The lighting conditions included were dark, dark but lighted, dusk, and dawn. We ended up with six crash types that would potentially benefit from the use of UVA headlights at night. These crash geometries included 1) crashes where a pedestrian or bicyclist was involved (which will be referred to as pedestrian crashes) ; 2) crashes occurring in a construction or maintenance zone; 3) crashes occurring on entrance and exit ramps of interstates; 4) single vehicle roadway departure crashes; 5) 2-vehicle opposite direction crashes where collisions include head-on and offset frontal; and 6) sideswipe crashes with both vehicle traveling straight where a driver fails to hold his/her lane.   Table 2 presents total crash cost by crash geometry.

Table 2. Crash costs by crash geometry[a]

Crash Geometry	Total Crash Costs (1995$)
Pedestrian Crashes	$13,900 million
Single Vehicle Road Departure	$27,800 million
Opposite Direction Crashes	$8,845 million
Interstate, on/off ramp	$1,330 million
Work Zone Crashes	$700 million
Sideswipe, vehicle straight	$590 million
All crashes	$53,200 million

[a] Crashes include those in light conditions other than daylight.

Because UVA headlights alone would increase the visibility of pedestrians and pedal cyclists, a 19% reduction in nighttime pedestrian crashes will pay for the additional headlight costs. Alternatively, a 5.5% reduction in all relevant nighttime crashes will pay for the costs of UVA headlights and fluorescent highway paint combined.   We also looked at other combinations and found that a 10% reduction in nighttime pedestrian crashes and a 4% reduction in the remaining relevant nighttime crashes will pay for the costs of UVA headlights and fluorescent highway paint.

This evaluation of UVA/fluorescent technology found that increases in detection and recognition distances of pedestrians and pedal cyclists ranged from 33 percent to 117 percent. There is currently no literature regarding the relationship between increased detection and recognition distances and crash reduction. However, if we assume that pedestrian crashes can be reduced by 33% (the value of the lowest measured improvement in recognition distances), we would achieve a benefit-cost ratio of 1.7 for UVA headlights.

Improvements in detection and recognition were also found for roadway delineation. These improvements ranged from 14% for right curve delineation to 48% for a no passing zone. If we assume that nighttime crashes, including those with pedestrians, are reduced by 14% (the value of the lowest improvement), we would achieve a benefit-cost ratio of 1.9 for UVA headlights and fluorescent striping. Table 3 presents the benefit-cost ratio for the different scenarios of reductions in nighttime crashes.

Table 3 - Benefit Cost Ratio for UVA Headlights and Fluorescent Striping by Percentage Reduction in Nighttime Crashes [a]

	% Reduction in Other Relevant Nighttime Crashes				
% **Reduction in Pedestrian Crashes**	6%	9%	12%	15%	25%
10%	1.2	1.7	2.1	2.6	3.9
15%	1.5	2.0	2.4	2.8	4.2
20%	1.7	2.2	2.6	3.0	4.4
25%	2.0	2.5	2.9	3.3	4.7
33%	2.4	2.8	3.3	3.7	5.1
50%	3.2	3.7	4.1	4.5	5.9

[a] Crashes include those in light conditions other than daylight.

COMMENTS AND CONCLUSIONS

Field tests have shown that the use of UVA/fluorescent technology improves both detection and recognition of roadside features and pedestrians at night and offers significant potential to reduce crashes. Only small decreases in relevant nighttime crashes will be required to pay for the estimated increased costs to implement the technology. An analysis of a vision enhancement system indicated that there were was a potential crash reduction range from 6.2% to 12.6% of night crashes.[Taylor, Abdel-Rahim, Narupiti, 1996] Our analysis showed that a reduction of 9% would result in a benefit cost ratio of 1.7.

In 1997, more than half of pedestrian deaths occurred during nighttime hours. [IIHS, 1998] The field study results reported detection distances improved 34% to 117% and recognition from 37% to 68% for five different pedestrian scenes using UVA headlights. A reduction of 19% of all pedestrian crashes would result in a cost-benefit ratio of one. In addition one of the most impressive improvements in the field study was the detection distance of a fluorescent bicycle; an improvement of 287%. Fifty percent of bicyclist deaths occur between 6pm and 6 am. [IIHS, 1998] UVA headlights have great potential to reduce pedestrian and bicycle crashes.

UVA headlights may also help older drivers at night. A positive effect on the visibility of pedestrians and on road design elements was demonstrated by Staehl et al.,[6] who tested two systems developed to enhance visibility during night-time driving: the Volvo ultraviolet light system and the Jaguar night vision system. The researchers concluded that using these systems could give older drivers more confidence when driving at night and should improve both their own safety and that of other vulnerable road users such as pedestrians.

A limitation of our study is that cost of UVA headlights and fluorescent paint and the reduction in crashes are estimates. We did not estimate the costs associated with fluorescent thermoplastic (as opposed to fluorescent paint) but assume that if mass produced, the increased cost of this material would be similar to the increased cost of highway striping paint. If the headlight cost were reduced to $50 per vehicle due to mass production, a benefit cost ratio of 2 would be achieved with 15% reduction in nighttime pedestrian crashes and a 3% reduction in other relevant nighttime crashes. Another limitation is that changes in driver behavior as a result of using UVA technology were not taken into account.

These findings suggest that it is possible that the use of UVA headlamps in automobiles might increase highway safety by increasing visibility without increasing glare from oncoming cars. More field work is need in this area to obtain better estimates of visibility improvements and to determine how increases in visibility translate into crash reduction.

We acknowledge that further work is needed, however, to establish the relationships between ostensible driver aids and crashes. In addition, more research involving UVA technology is needed for its successful implementation; however the real life-saving benefits of this technology should be pursued.

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